NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3883

PROPELLANT VAPORIZATION AS A CRITERION FOR ROCKET-ENGINE DESIGN; CALCULATIONS OF CHAMBER LENGTH TO VAPORIZE VARIOUS PROPELLANTS

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SUMMARY

Vaporization rates were calculated for drops of n-heptane, ammonia, hydrazine, oxygen, and fluorine. The percent propellant vaporized is correlated with an effective chamber length for various spray conditions, and various engine-design and operating parameters. The results show that the effective chamber length required to vaporize a given high percentage of propellant is the shortest with oxygen and increases for fluorine, heptane, ammonia, and hydrazine in that order.

INTRODUCTION

Calculations were reported in references 1 and 2 for the rate of fuel vaporization in the combustion chamber of a n-heptane - oxygen rocket engine. How the vaporization-rate calculations could be used to predict combustion efficiencies and to design combustors was also indicated. The results of these calculations, based on a combustion model in which vaporization of the fuel was rate controlling, showed how various design- and operating-parameter changes would affect the vaporization rates of n-heptane drops burning in oxygen. Reference 2 also indicated that a small number of large drops that do not vaporize completely may be responsible for much of the loss in rocket-engine performance. Experimental results obtained with an engine (ref. 3) using n-heptane as the fuel agreed with the calculations for sprays having geometric standard deviations of 2.5 and mass median drop radii of 70 to 280 microns depending on the type of injector.

This report covers the additional calculations made at the NACA Lewis laboratory to determine the vaporization rates of oxygen, fluorine, ammonia, and hydrazine in rocket engines. The results are presented in terms of an effective chamber length required to vaporize a given percent of the propellant. The analysis assumes that the vaporizing propellant is burned instantaneously at stoichiometric conditions. The analysis further assumes that there is one-dimensional steady-state flow and that all drops are produced at the injector face and have equal velocities. The model and equations of reference 1 are used to determine the velocity, mass, and temperature of the individual drops at various distances downstream.

METHOD

The calculation used the model, the iteration technique, and the following equations from references 1 and 2:

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Mass-transfer rate,

$$w = AKp\alpha \tag{1}$$

Heat-transfer rate,

$$q_v = Ah(T - T_l)Z \tag{2}$$

Drop-heating rate,

$$\frac{dT_l}{d\theta} = \frac{q_v - w\lambda}{m_i c_{p,l}} \tag{3}$$

Drop acceleration,

$$\frac{dv}{d\theta} = -\frac{3}{8}\frac{C_D \rho_{mx} U^2}{\rho_l r} \tag{4}$$

Gas velocity,

$$\frac{u}{u_{fin}} = 1 - \frac{\sum n_i m_i}{\sum n_i m_{i,o}} \tag{5}$$

Drop-size distribution,

$$\frac{dR}{dr} = \frac{a'}{r}\exp\left\{-\frac{1}{2}\left[\frac{\ln\left(\frac{r}{M_{g,M}}\right)}{\ln \sigma_g}\right]^2\right\} \tag{6}$$

For calculation purposes the propellant was assumed to be in five drop-size groups, which were arbitrarily chosen from equation (6) as those equal to 10, 30, 50, 70, and 90 percent of the mass in drops smaller than the drop radius. With a median drop radius of 75 microns and a standard deviation of 2.3 the five drop radii selected by this method were 25, 48, 75, 120, and 225 microns. The number of drops in each group was so chosen that each group had 20 percent of the total mass. The symbols used in this report are defined in appendix A.

The equations were solved by an iterative procedure as described in reference 4. The average physical properties in the mantle surrounding the drop were also determined by the method described in reference 4. Table I shows the design and operating conditions used in the calculations. Appendix B shows equations used to describe the physical properties for heptane, ammonia, and hydrazine vaporizing in a gaseous-oxygen atmosphere, oxygen vaporizing in a gaseous-heptane atmosphere, and fluorine vaporizing in a gaseous-hydrogen atmosphere.

RESULTS AND DISCUSSION

The results of the calculations are droplet histories, examples of which are shown in figure 1. Droplet temperature, droplet velocity, gas velocity, percentage of mass vaporized, and vaporization rate are shown at various chamber lengths for n-heptane, ammonia, hydrazine, oxygen, and fluorine. The conditions used in the calculations shown in figure 1 are indicated in table I. The initial temperature of heptane and hydrazine was taken at room temperature. Ammonia was arbitrarily taken at its normal boiling point while the initial temperature for fluorine and oxygen corresponds to the normal boiling point of nitrogen. The effect of selecting other temperatures and conditions is indicated in reference 1 and later in the Correlation of Results section.

Temperature Histories

The temperature histories of the small drops (25 microns), median drops (75 microns), and large drops (225 microns) in the spray are shown in figure 1(a) for five propellants. The calculated temperatures rise to a steady value corresponding to a wet-bulb temperature. The wet-bulb temperature and corresponding vapor pressure are tabulated in the following table for the various propellants. Also tabulated is the ratio of the distance required to attain the wet-bulb temperature to the distance required to vaporize the drop.

Propellant	Wet-bulb temperature, $^{\circ}$R	Vapor pressure at wet bulb, lb/sq in.	$\frac{\text{Length to wet bulb}}{\text{Length to vaporize}}$
Heptane	845	133	1/6
Hydrazine	860	165	1/15
Ammonia	555	205	1/15
Oxygen	235	275	1/15
Fluorine	220	255	1/15

Gas-Velocity Histories

The average velocity of the vaporized and burned propellant at various positions down the chamber is shown in figure 1(b). For all propellants this gas velocity initially increases rapidly and then asymptotically approaches the final gas velocity. The gas-velocity curves for oxygen and fluorine are about the same (liquid oxygen being slightly higher than fluorine) and were higher than the other three propellants. The lowest gas velocity curve was obtained with hydrazine. The ranking order of propellants with respect to decreasing gas velocity at a fixed chamber length was (1) oxygen, (2) fluorine, (3) n-heptane, (4) ammonia, and (5) hydrazine.

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Droplet-Velocity Histories

Droplet-velocity curves for the small-, median-, and large-diameter drops are shown in figure 1(c) for the five propellants. The velocity of the drop when it is 99 percent vaporized is indicated by the solid symbol. The lowest velocity at complete vaporization was obtained with the high-density fluorine. The small drops accelerate faster than the larger drops; thus, a mixing effect occurs because of the relative motion of the drops.

Mass Histories

Curves showing the percent mass vaporized of the small, median, and large drops in the spray as well as the average for the spray are shown in figure 1(d) for the five different propellants. The order of the propellants, based on vaporization rate, was (1) oxygen, (2) fluorine, (3) n-heptane, (4) ammonia, and (5) hydrazine. The shapes of all the curves were similar with the exception of n-heptane which crosses the ammonia curves. The curves show that in 2 inches the small drops of all propellants are almost completely vaporized. However, in 2 inches only a small percentage of the large drops was vaporized.

Vaporization-Rate Histories

The total-vaporization-rate per unit-length curves (fig. 1(e)) are similar to those shown in references 1 and 2. There are two peak points and a minimum for each propellant. The highest peak vaporization rate is obtained with fluorine. Second highest peak is with oxygen, third with ammonia, fourth with heptane, and the lowest peak occurs with hydrazine. The peak values occur at different positions in the chamber with the various propellants. The peak occurs closest to the injector face with oxygen and fluorine. The peak is the farthest from the injector with heptane and hydrazine. Ammonia falls between the two extremes.

Correlation of Results

The calculated results obtained for the conditions listed in table I were correlated for each propellant. Percent mass vaporized and unvaporized curves for sprays having a standard deviation σ_g of 2.3 were plotted against effective length in figure 2 for each propellant. This deviation represents a spray in which 68.23 percent of the mass is in the drop-size range between $M_{g,M}/\sigma_g$ and $\sigma_g M_{g,M}$. The correlation of results was accomplished by modifying chamber length with a factor to obtain an effective length.

$$\text{Effective length} = \frac{LP^{0.66}u_{fin}^{0.40}1.9\times10^{-5}}{(1 - T_r)^{0.40}M_{g,M}^{1.45}v_o^{0.75}}$$

This factor was obtained from crossplots of the lengths required to vaporize 90 percent of the mass. The correction factor is slightly different from that determined in references 1 and 2. The critical temperature was used to obtain a reduced initial temperature T_r. The term $(1 - T_r)$ was used to indicate that the model of vaporization does not apply when the initial temperature is greater than the critical temperature (in this situation $T_r > 1$ and a negative effective length is obtained). In addition to these changes, it was found that the exponents on pressure and final gas velocity obtained for heptane in references 1 and 2 did not fit all propellants; therefore, new exponents were determined for these parameters.

The spread in the effective length required to achieve a given percent vaporized was greatest in the 20- to 30-percent vaporized region as was also found in references 1 and 2. The variation in the position of the inflection point in the mass vaporized curve produced most of the spread. The plot of percent-mass unvaporized as a function of effective length gave almost a single curve for each propellant.

Correlated results for various standard deviations of the five propellants are shown in figure 3. With all propellants, increasing the standard deviation of the spray increased the effective length required to vaporize a given high percentage of the propellant. The lines in figure 3 represent the log mean effective length for various operating conditions. The results of cold-flow spray studies (ref. 5) indicate that rocket-engine sprays have a standard deviation of about 2.3; therefore, the results shown in figure 2 should be applicable to most rocket-engine systems. This was verified in the comparison of experimental and calculated results of reference 2.

CONCLUDING REMARKS

Calculations were made to determine the vaporization rates of liquid drops for n-heptane, ammonia, hydrazine, oxygen, and fluorine. The calculations were made for each propellant with various spray conditions, and various engine-design and operating parameters to show how these variables would affect the vaporization rate and chamber length required to vaporize the drops. The results are correlated by an effective length for each propellant. The calculations have shown that the effective length required to vaporize a given high percentage of propellant is the shortest with oxygen and increases for fluorine, n-heptane, ammonia, and hydrazine, in that order.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, June 2, 1958

APPENDIX A

SYMBOLS

A	surface area of drop, sq in.
a'	constant for mass distribution, $\frac{100}{\sqrt{2\pi}\ \ln \sigma_g}$
C_D	coefficient of drag for spheres, dimensionless
c_p	specific heat at constant pressure, Btu/(lb)($^{\circ}$F)
D	diffusion coefficient, sq in./sec
h	heat-transfer coefficient, Btu/(sq in.)(sec)($^{\circ}$F)
K	coefficient of mass transfer, sec^{-1}
k	thermal conductivity, Btu/(in.)(sec)($^{\circ}$F)
L	chamber length, in.
M	molecular weight of propellant, lb/mole
$M_{g,M}$	mass median drop radius, in.
m_i	mass of "i" drop, lb
$m_{i,o}$	mass of "i" drop at beginning of time, lb
n_i	number of drops in group of "i" sized drops
P	chamber pressure, lb/sq in.
p	vapor pressure of liquid, lb/sq in.
q_v	heat-transfer rate of drop, Btu/sec
R	percent of mass in drops smaller than "r"
r	drop radius, in.
T	temperature of gas, $^{\circ}$R

T_c critical temperature of propellant, $^{\circ}R$

T_l temperature of liquid drop, $^{\circ}R$

T_r reduced temperature, $T_{l,o}/T_c$

$\overline{T}$ mean gas temperature, $^{\circ}R$

U velocity difference between gas and drop, in./sec

u velocity of gas in chamber, in./sec

u_{fin} final velocity of gas, in./sec

v droplet velocity, in./sec

w vaporization rate of fuel, lb/sec

Z correction factor for heat transfer, dimensionless

α correction factor for mass transfer, dimensionless

θ time, sec

λ latent heat of vaporization, Btu/lb

μ viscosity, lb/(in.)(sec)

ρ density, lb/cu in.

σ_g geometric standard deviation, $\frac{r \text{ at } R = 84.13}{r \text{ at } R = 50.0}$

Subscripts:

l liquid fuel

mx vapor mixture

o initial condition

p combustion products

v vapor mixture

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APPENDIX B

PHYSICAL PROPERTIES

Heptane with Gaseous Oxygen

Density of liquid,

$$\rho_l = 3.1662\times10^{-2} - 9.5355\times10^{-6}T_l - 6.945\times10^{-9}T_l^2, \text{ lb/cu in.}$$

Heat of vaporization,

$$\lambda = 139.9 + 0.181\ T_l - 2.7875\times10^{-4}T_l^2, \text{ Btu/lb}$$

Specific heat of liquid,

$$c_{p,l} = 0.231 + 5.62\times10^{-4}T_l, \text{ Btu/(lb)(}^{\circ}\text{F)}$$

Specific heat of heptane vapor,

$$c_{p,v} = 0.5755 + 1.805\times10^{-4}\overline{T}, \text{ Btu/(lb)(}^{\circ}\text{F)}$$

Specific heat of combustion products,

$$c_{p,p} = 0.2898 + 4.07\times10^{-5}\overline{T}, \text{ Btu/(lb)(}^{\circ}\text{F)}$$

Thermal conductivity of heptane vapor,

$$k_v = 2.914\times10^{-8} + 5.847\times10^{-11}\overline{T}, \text{ Btu/(in.)(sec)(}^{\circ}\text{F)}$$

Thermal conductivity of combustion products,

$$k_p = 1.3349\times10^{-7} + 3.4111\times10^{-10}\overline{T}, \text{ Btu/(in.)(sec)(}^{\circ}\text{F)}$$

Vapor pressure,

$$\ln p = 11.94763 - 5255.89687/(T_l - 101.58), \text{ lb/sq in.}$$

Viscosity of heptane vapor,

$$\mu_v = 2.106\times10^{-7} + 7.690\times10^{-10}\overline{T}, \text{ lb/(in.)(sec)}$$

Viscosity of combustion products,

$$\mu_p = 5.5615\times10^{-7} + 1.4214\times10^{-9}\overline{T}, \text{ lb/(in.)(sec)}$$

Diffusion coefficient of vapor mixture,

$$D = \left[-9.815\times10^{-4} + 1.973\times10^{-6}\overline{T} + 1.1319\times10^{-9}(\overline{T})^2\right]\frac{300}{P}, \text{ sq in./sec}$$

Molecular weight of combustion products,

$$M_p = 31, \text{ lb/mole}$$

Oxygen with Gaseous Heptane

Density of liquid,

$$\rho_l = 0.023079 + 2.7359\times10^{-4}T_l - 9.9465\times10^{-7}T_l^2, \text{ lb/cu in.}$$

Heat of vaporization,

$$\lambda = 61.332 + 0.5916\ T_l - 2.48\times10^{-3}T_l^2, \text{ Btu/lb}$$

Specific heat of liquid,

$$c_{p,l} = 0.3726 + 2.0482\times10^{-4}T_l, \text{ Btu/(lb)(}^{\circ}\text{F)}$$

Specific heat of oxygen vapor,

$$c_{p,v} = 0.21333 + 2.2111\times10^{-5}\overline{T}, \text{ Btu/(lb)(}^{\circ}\text{F)}$$

Specific heat of combustion products,

$$c_{p,p} = 0.2898 + 4.07\times10^{-5}\overline{T}, \text{ Btu/(lb)(}^{\circ}\text{F)}$$

Thermal conductivity of oxygen vapor,

$$k_v = 2.6611\times10^{-7} + 3.4057\times10^{-10}\overline{T}, \text{ Btu/(in.)(sec)(}^{\circ}\text{F)}$$

Thermal conductivity of combustion products,

$$k_p = 1.3349\times10^{-7} + 3.4111\times10^{-10}\overline{T}, \text{ Btu/(in.)(sec)(}^{\circ}\text{F)}$$

Vapor pressure,

$$\ln p = 11.9584 - \frac{1476.4912}{(T_l - 3.5680)}, \text{ lb/sq in.}$$

Viscosity of oxygen vapor,

$$\mu_v = 2.2500\times10^{-7} + 1.1702\times10^{-9}\bar{T},\ \text{lb/(in.)(sec)}$$

Viscosity of combustion products,

$$\mu_p = 5.5615\times10^{-7} + 1.4214\times10^{-9}\bar{T},\ \text{lb/(in.)(sec)}$$

Diffusion coefficient of vapor mixture,

$$D = \left[-2.36396\times10^{-3} + 5.7897\times10^{-6}\bar{T} + 2.87685\times10^{-9}(\bar{T})^2\right]\frac{300}{P},\ \text{sq in./sec}$$

Molecular weight of combustion products,

$$M_p = 31,\ \text{lb/mole}$$

Ammonia with Gaseous Oxygen

Density of liquid,

$$\rho_l = 3.13955\times10^{-2} - 6.0219\times10^{-6}T_l - 2.23169\times10^{-8}T_l^2,\ \text{lb/cu in.}$$

Heat of vaporization,

$$\lambda = 676.362 + 0.32247\ T_l - 1.210\times10^{-3}T_l^2,\ \text{Btu/lb}$$

Specific heat of liquid,

$$c_{p,l} = 0.8314 + 5.7993\times10^{-4}T_l,\ \text{Btu/(lb)(}^{\circ}\text{F)}$$

Specific heat of ammonia vapor,

$$c_{p,v} = 0.60931 + 8.31361\times10^{-5}\bar{T},\ \text{Btu/(lb)(}^{\circ}\text{F)}$$

Specific heat of combustion products,

$$c_{p,p} = 0.403578 + 6.996\times10^{-6}\bar{T},\ \text{Btu/(lb)(}^{\circ}\text{F)}$$

Thermal conductivity of ammonia vapor,

$$k_v = 4.6853\times10^{-7} + 3.551\times10^{-10}\bar{T},\ \text{Btu/(in.)(sec)(}^{\circ}\text{F)}$$

Thermal conductivity of combustion products,

$$k_p = 5.10692\times10^{-8} + 7.616145\times10^{-10}\bar{T},\ \text{Btu/(in.)(sec)(}^{\circ}\text{F)}$$

Vapor pressure,

$$\ln p = 13.1485 - \frac{3899.209}{(T_l - 58.2354)},\ \text{lb/sq in.}$$

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Viscosity of ammonia vapor,

$$\mu_v = 1.07097\times10^{-6} + 8.11607\times10^{-10}\bar{T},\ \text{lb/(in.)(sec)}$$

Viscosity of combustion products,

$$\mu_p = 1.64352\times10^{-7} + 2.45252\times10^{-9}\bar{T},\ \text{lb/(in.)(sec)}$$

Diffusion coefficient,

$$D = (-4.87304\times10^{-2} + 4.01198\times10^{-5}\bar{T} - 8.358\times10^{-10}\bar{T}^2)\ \frac{300}{P},\ \text{sq in./sec}$$

Molecular weight of combustion products,

$$M_p = 24,\ \text{lb/mole}$$

Hydrazine with Gaseous Oxygen

Density of liquid,

$$\rho_l = 3.062318\times10^{-2} + 4.028897\times10^{-5}T_l - 5.54321\times10^{-8}T_l^2,\ \text{lb/cu in.}$$

Heat of vaporization,

$$\lambda = 730.747 - 0.3591305\ T_l + 1.214\times10^{-4}T_l^2,\ \text{Btu/lb}$$

Specific heat of liquid,

$$c_{p,l} = 0.589125 + 2.80708\times10^{-4}T_l,\ \text{Btu/(lb)(}^{\circ}\text{F)}$$

Specific heat of hydrazine vapor,

$$c_{p,v} = 0.3360 + 1.804\times10^{-4}\bar{T},\ \text{Btu/(lb)(}^{\circ}\text{F)}$$

Specific heat of combustion products,

$$c_{p,p} = 0.403578 + 6.996\times10^{-6}\overline{T}, \text{ Btu/(lb)(}^{\circ}\text{F)}$$

Thermal conductivity of hydrazine vapor,

$$k_v = 1.23753\times10^{-8} + 2.230358\times10^{-10}\overline{T}, \text{ Btu/(in.)(sec)(}^{\circ}\text{F)}$$

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Thermal conductivity of combustion products,

$$k_p = 5.10692\times10^{-8} + 7.616145\times10^{-10}\overline{T}, \text{ Btu/(in.)(sec)(}^{\circ}\text{F)}$$

Vapor pressure,

$$\ln p = 14.328787 - \frac{7363.22}{(T_l - 63.1713)}, \text{ lb/sq in.}$$

Viscosity of hydrazine vapor,

$$\mu_v = 4.19981\times10^{-8} + 9.581164\times10^{-10}\overline{T}, \text{ lb/(in.)(sec)}$$

Viscosity of combustion products,

$$\mu_p = 1.64352\times10^{-7} + 2.45252\times10^{-9}\overline{T}, \text{ lb/(in.)(sec)}$$

Diffusion coefficient of vapor mixture,

$$D = (-5.3537\times10^{-4} + 3.13874\times10^{-6}\overline{T} + 3.37045\times10^{-9}\overline{T}^2)\frac{300}{P}, \text{ sq in./sec}$$

Molecular weight of combustion products,

$$M_p = 24, \text{ lb/mole}$$

Fluorine with Gaseous Hydrogen

Density of liquid,

$$\rho_l = 6.846\times10^{-2} - 3.036\times10^{-5}T_l - 3.9308\times10^{-7}T_l^2, \text{ lb/cu in.}$$

Heat of vaporization,

Specific heat of liquid,

$$c_{p,l} = 0.349 + 1.212\times10^{-4}T_l, \text{ Btu/(lb)(}^{\circ}\text{F)}$$

Specific heat of fluorine vapor,

$$c_{p,v} = 0.223994 + 1.667\times10^{-6}\overline{T}, \text{ Btu/(lb)(}^{\circ}\text{F)}$$

Specific heat of combustion products,

$$c_{p,p} = 0.32332 + 2.068\times10^{-5}\overline{T}, \text{ Btu/(lb)(}^{\circ}\text{F)}$$

Thermal conductivity of fluorine vapor,

$$k_v = 2.7606\times10^{-7} + 3.47122\times10^{-10}\overline{T}, \text{ Btu/(in.)(sec)(}^{\circ}\text{F)}$$

Thermal conductivity of combustion products,

$$k_p = 1.0765\times10^{-7} + 4.31280\times10^{-10}\overline{T}, \text{ Btu/(in.)(sec)(}^{\circ}\text{F)}$$

Vapor pressure,

$$\ln p = 12.3171 - \frac{1482.9545}{(T_l - 2.5645)}, \text{ lb/sq in.}$$

Viscosity of fluorine vapor,

$$\mu_v = 1.2591\times10^{-6} + 1.584\times10^{-9}\overline{T}, \text{ lb/(in.)(sec)}$$

Viscosity of combustion products,

$$\mu_p = 2.60098\times10^{-7} + 1.04178\times10^{-9}\overline{T}, \text{ lb/(in.)(sec)}$$

Diffusion coefficient of vapor mixture,

$$D = \left[-4.5732\times10^{-3} + 1.078\times10^{-5}\overline{T} + 5.421\times10^{-9}(\overline{T})^2\right]\frac{300}{P}, \text{ sq in./sec}$$

Molecular weight of combustion products,

$$M_p = 20, \text{ lb/mole}$$

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2. Priem, Richard J.: Propellant Vaporization as a Criterion for Rocket-Engine Design; Calculations Using Various Log-Probability Distributions of Heptane Drops. NACA TN 4098, 1957.

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4. El Wakil, M. M., Uyehara, O. A., and Myers, P. S.: A Theoretical Investigation of the Heating-Up Period of Injected Fuel Droplets Vaporizing in Air. NACA TN 3179, 1954.

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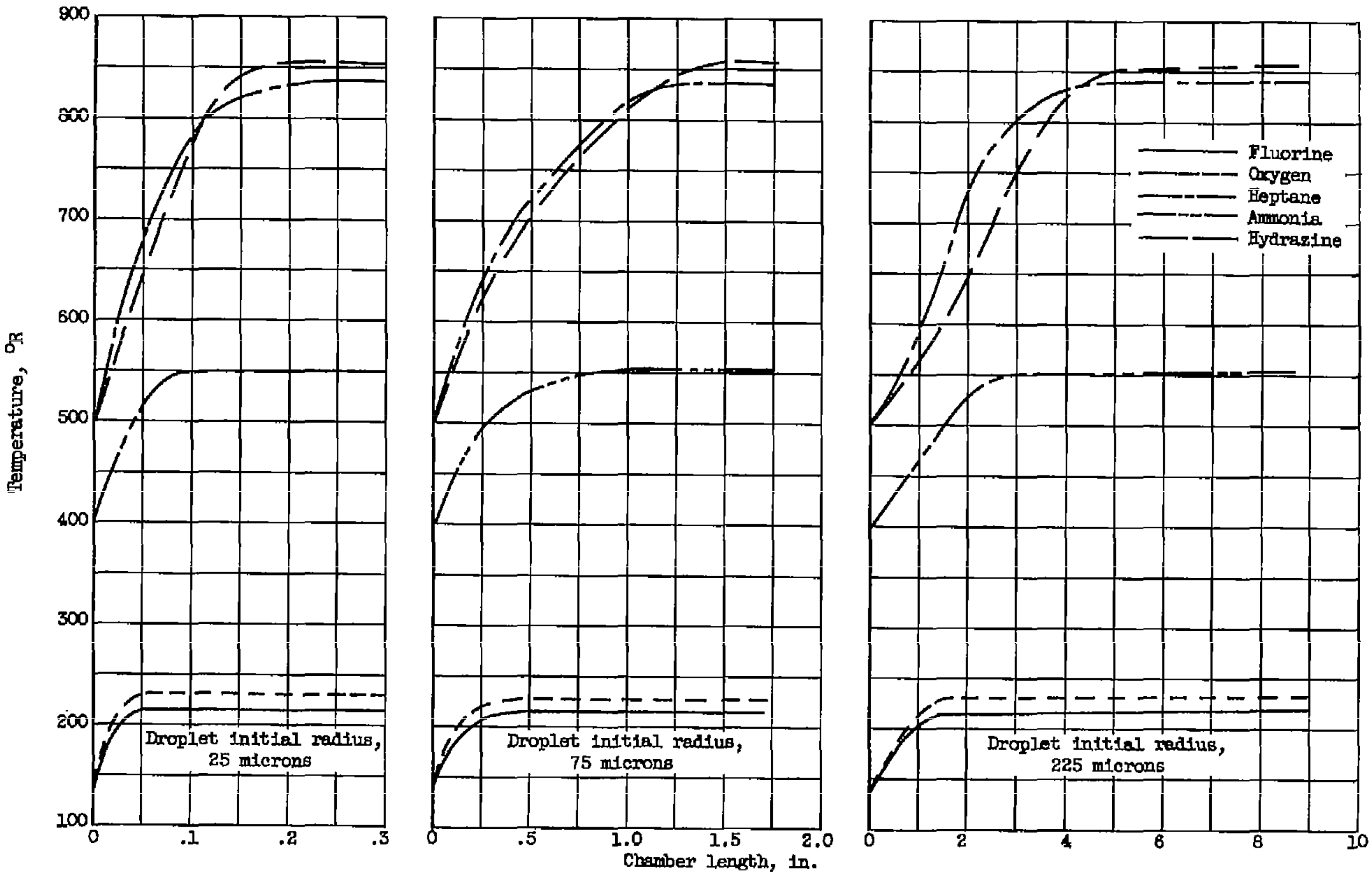
TABLE I. - RANGE OF CONDITIONS USED FOR CALCULATIONS

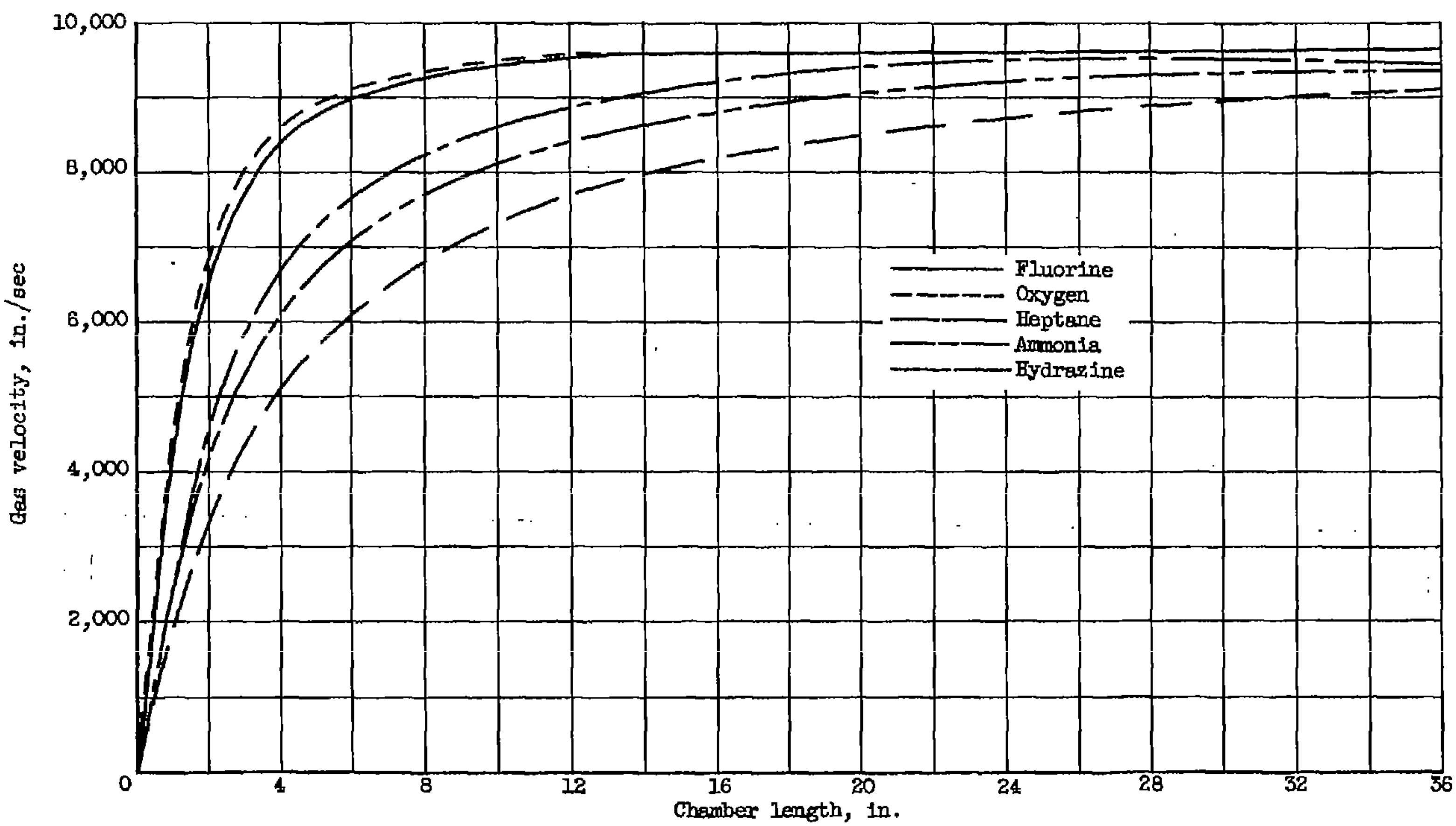
Initial drop temperature, °R					Mass median drop radius, M_g,M, microns	Geometric standard deviation, σ_g	Initial drop velocity, v_o, in./sec	Final gas velocity, u_{fin}, in./sec	Chamber pressure, p, lb/sq in.
Heptane	Ammonia	Hydrazine	Oxygen	Fluorine					
400	300				75	2.3	1200	9,600	300
[a]500	[a]400	[a]500	[a]140	[a]140	75	[a]2.3	[a]1200	[a]9,600	[a]300
					25	2.3	1200	9,600	300
					75	1.0	1200	9,600	300
						1.54	1200	9,600	300
						2.3	600	9,600	300
							1200	2,400	300
								9,600	150
									600
								19,200	300
							2400	9,600	300
						3.6	1200	9,600	300
					225	2.3	1200	9,600	300
700	500	700	220	220	75	2.3	1200	9,600	300

[a]Conditions used for calculations presented in figs. 1 to 5.



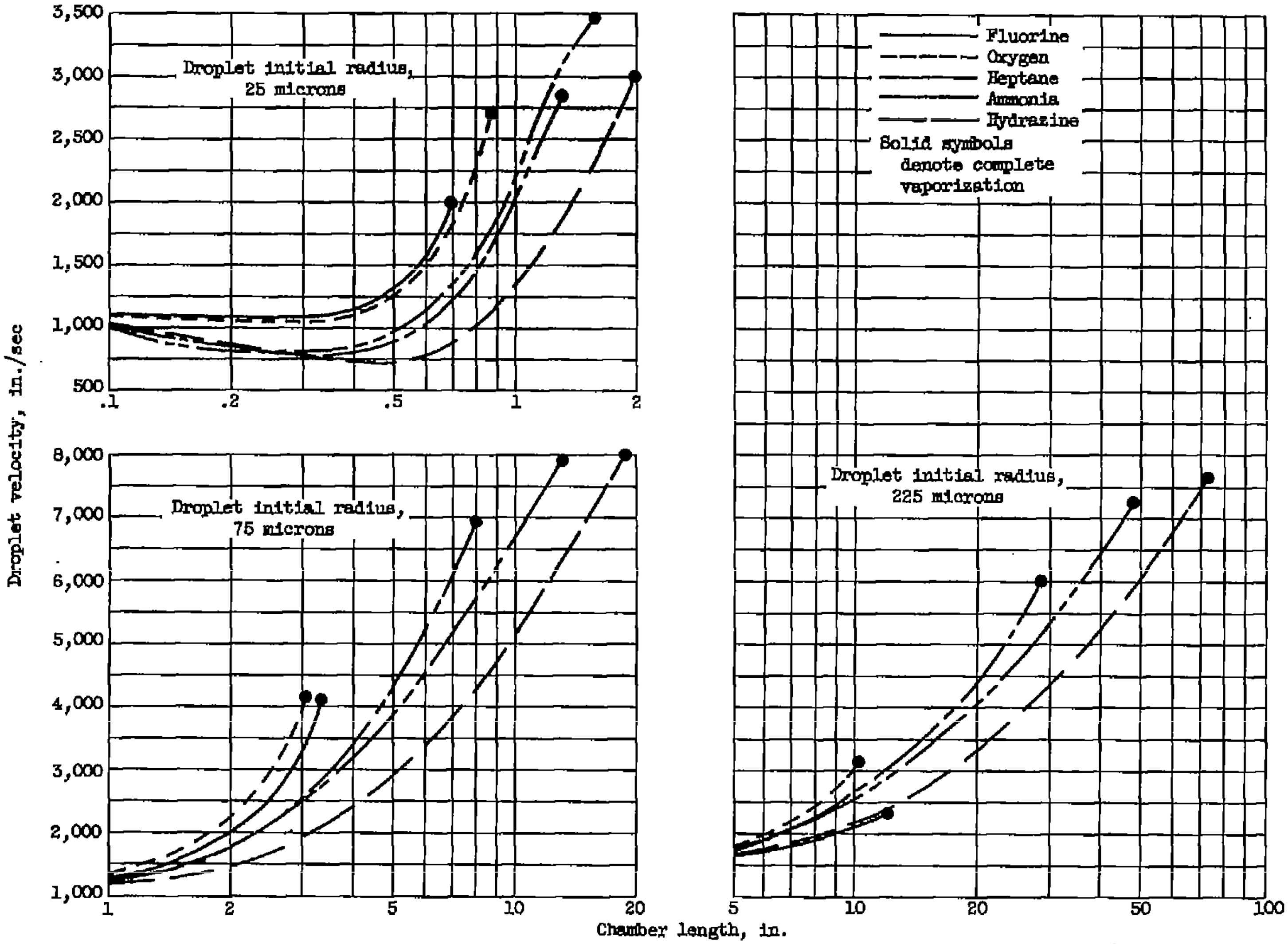
(a) Droplet-temperature histories.

Figure 1. - Typical droplet histories for various propellants (see table I for conditions).



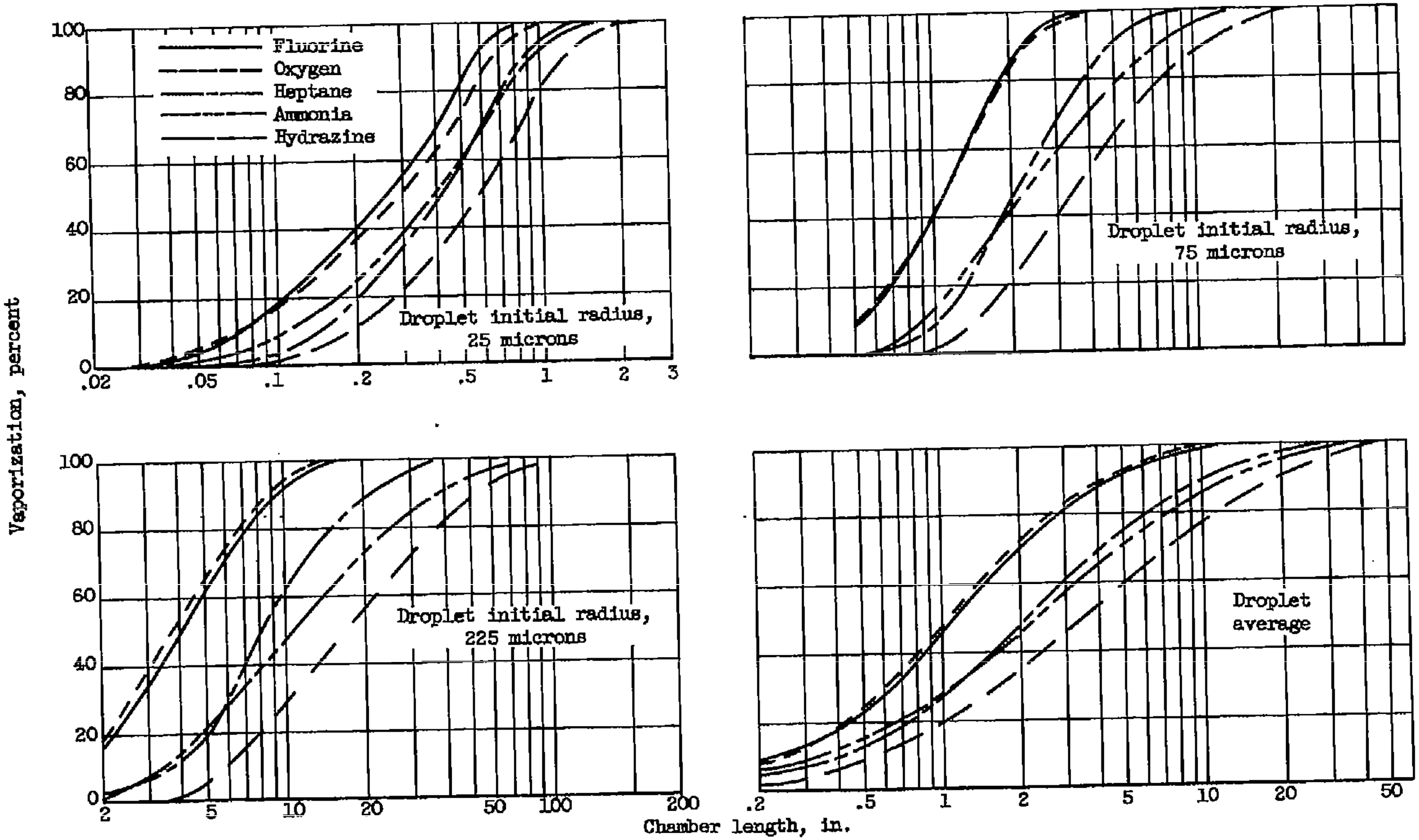
(b) Gas-velocity histories.

Figure 1. - Continued. Typical droplet histories for various propellants (see table I for conditions).



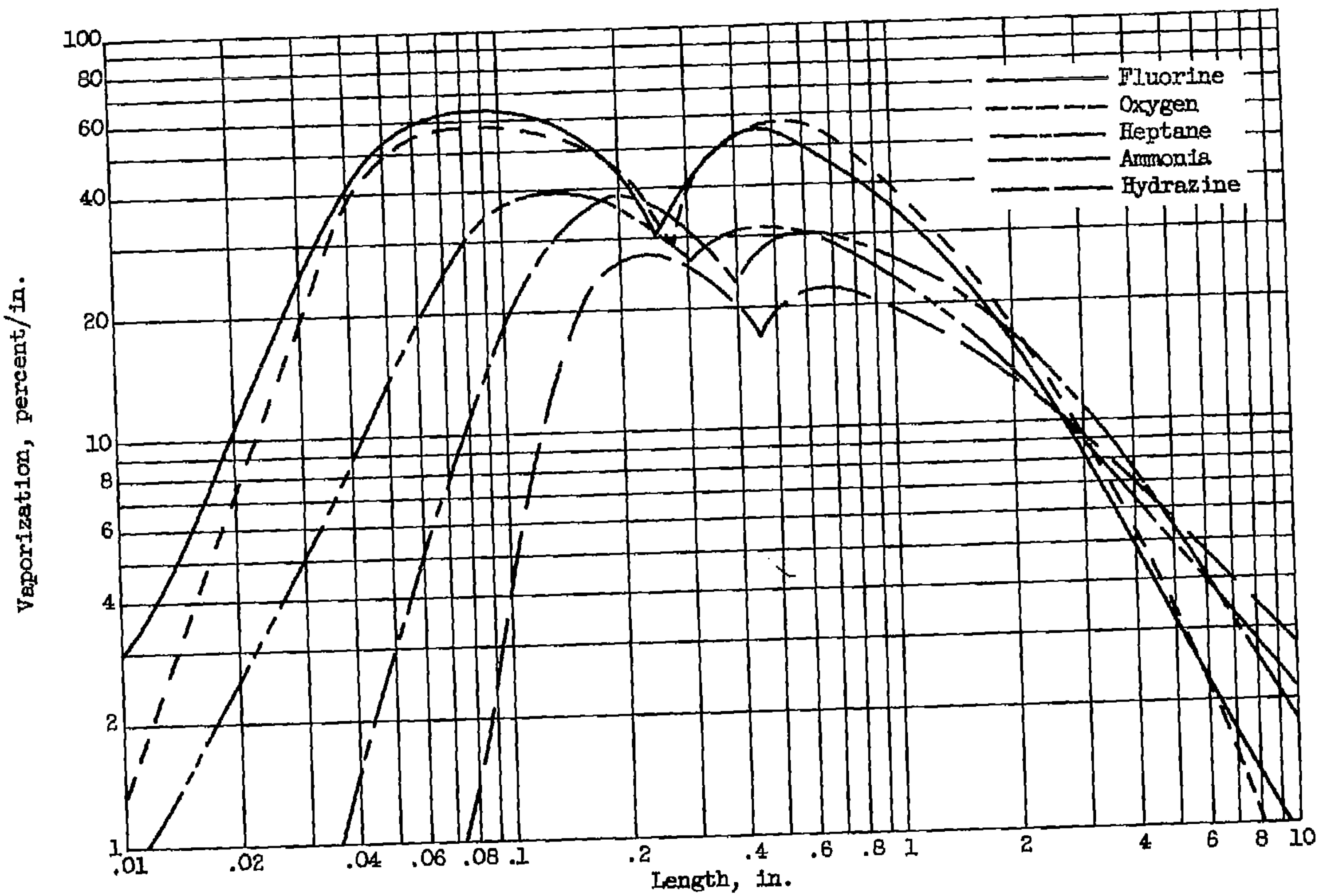
(c) Droplet-velocity histories.

Figure 1. - Continued. Typical droplet histories for various propellants (see table I for conditions).



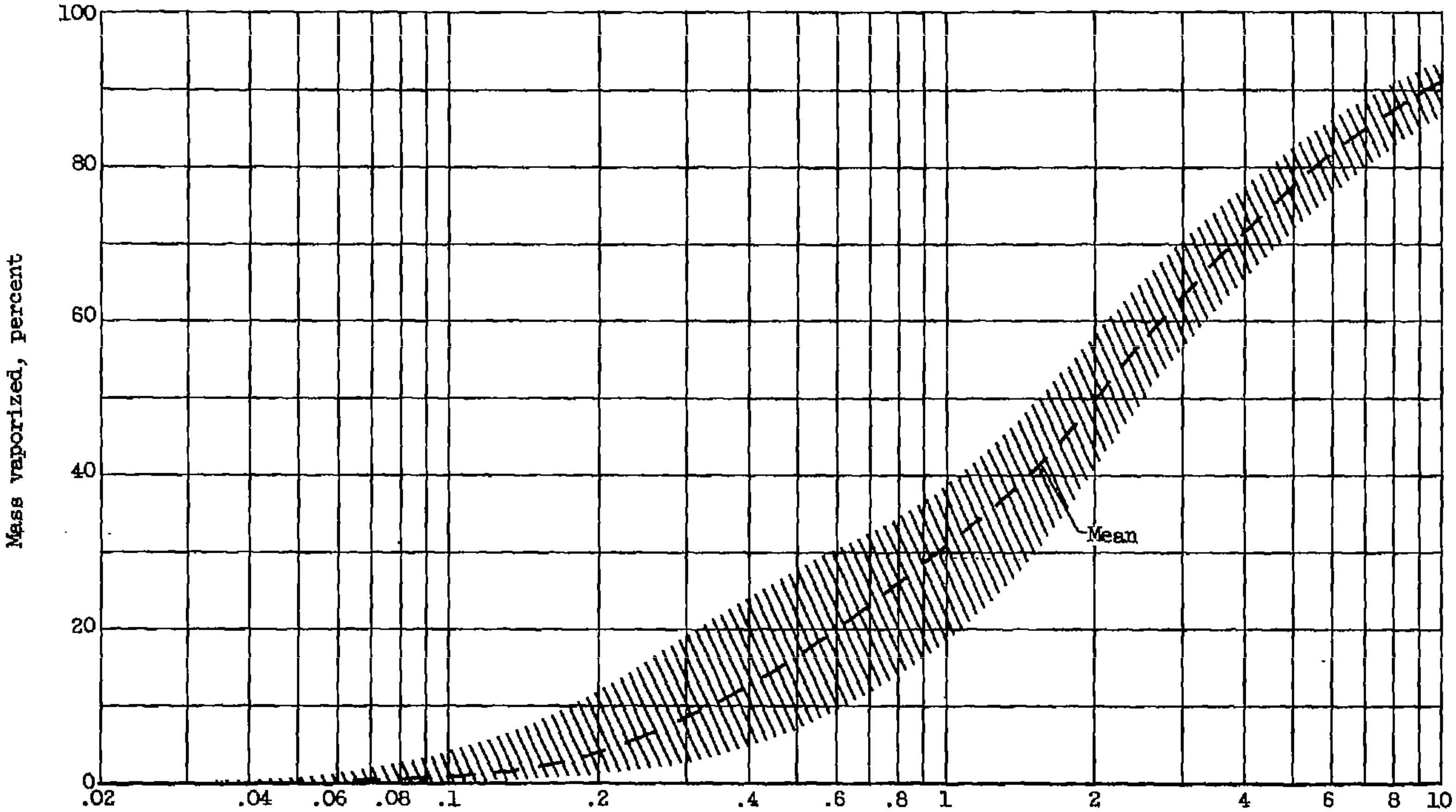
(d) Droplet-mass histories.

Figure 1. - Continued. Typical droplet histories for various propellants (see table I for conditions).



(e) Total vaporization rates.

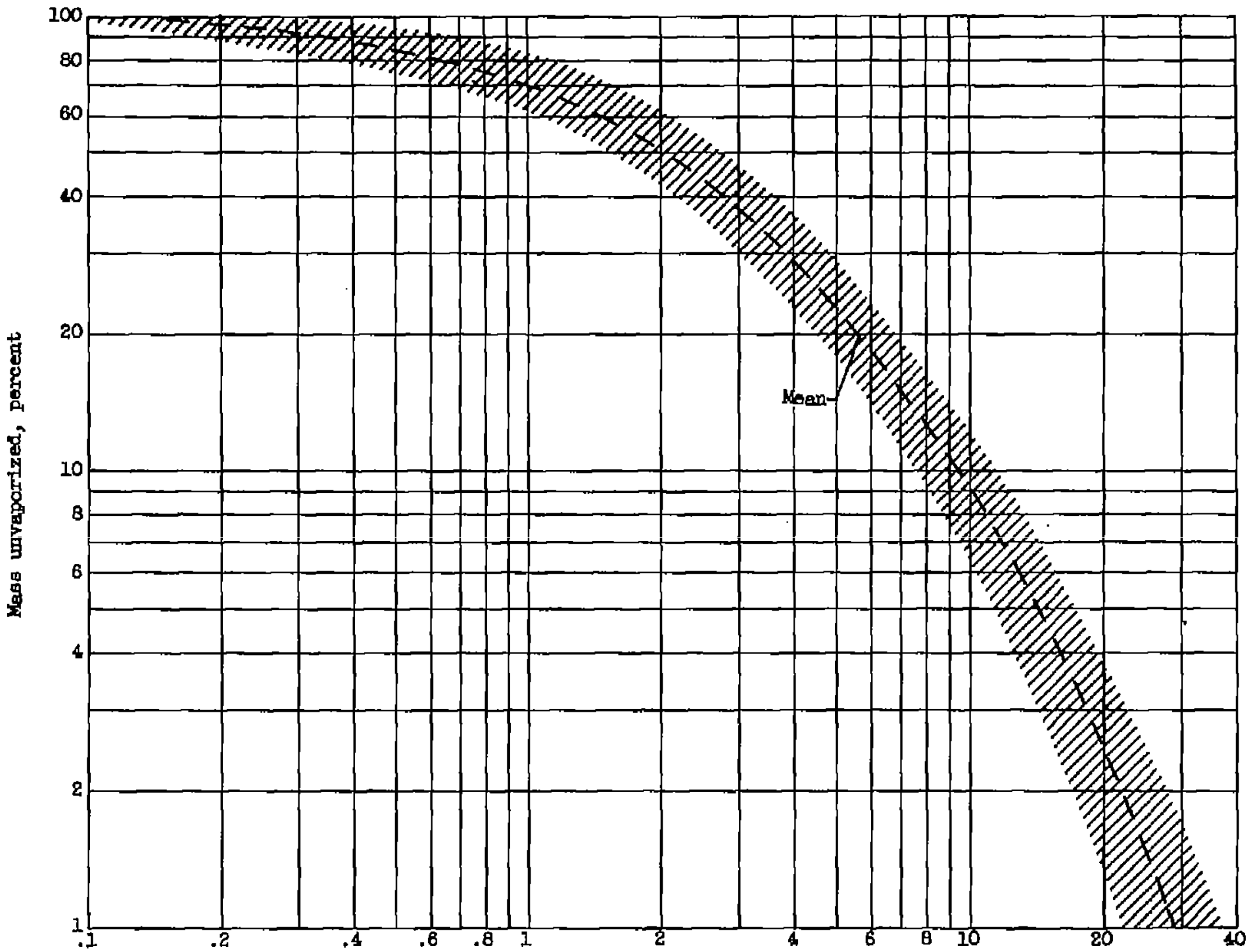
Figure 1. - Concluded. Typical droplet histories for various propellants (see table I for conditions).



$$\text{Effective length} = \frac{LP^{0.66} u_{fin}^{0.40} 1.9\times10^{-5}}{(1 - T_r)^{0.40} M_{g,M}^{1.45} v_0^{0.75}}, \ \frac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$$

(a) Mass vaporized for heptane.

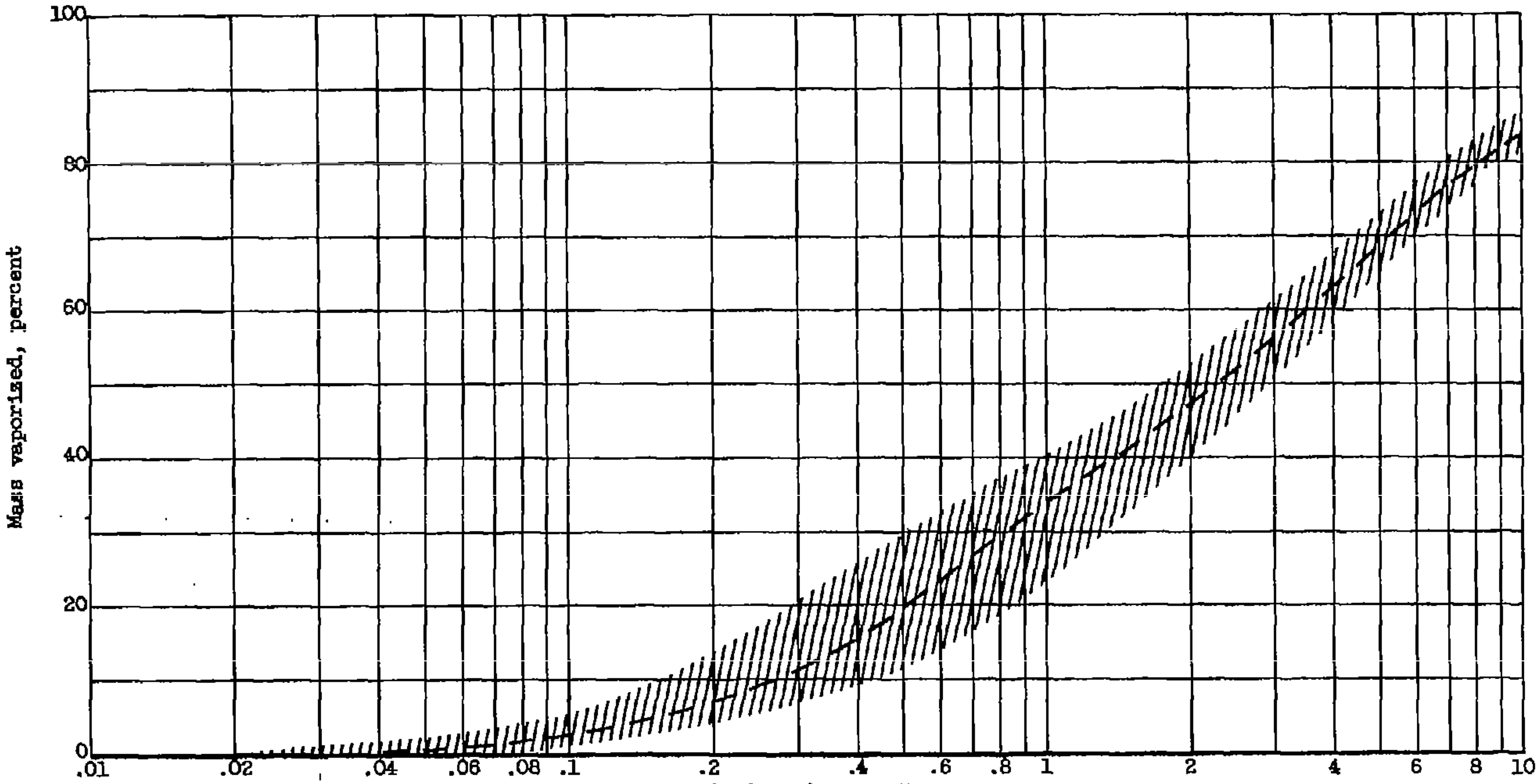
Figure 2. - Correlated results for propellant with standard deviation of 2.3.



$$\text{Effective length} = \frac{LP^{0.66}u_{f,in}^{0.40}1.9\times10^{-5}}{(1 - T_r)^{0.40}M_{g,M}^{1.45}V_0^{0.75}},\ \frac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$$

(b) Mass unvaporized for heptane.

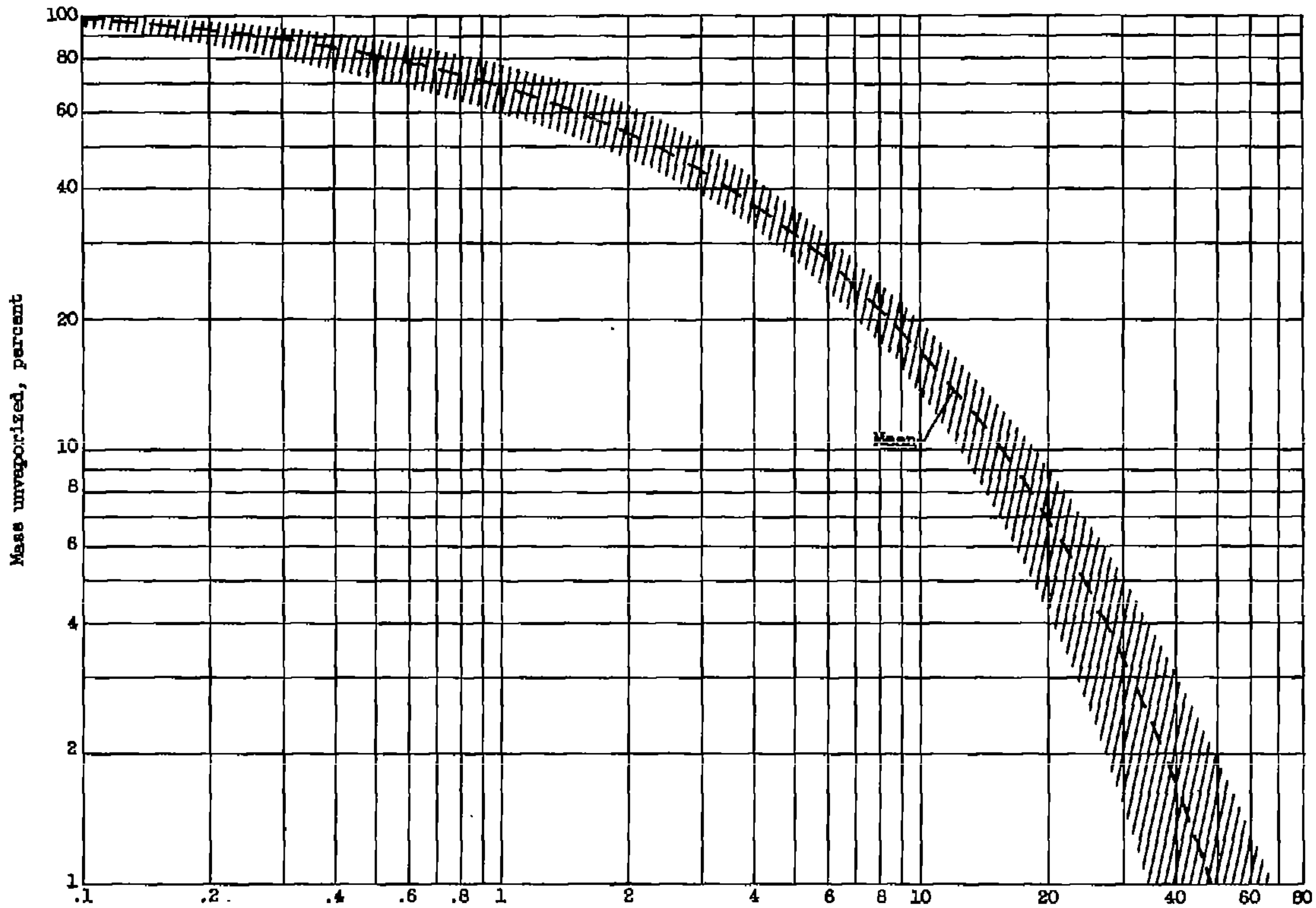
Figure 2. - Continued. Correlated results for propellant with standard deviation of 2.3.



Effective length $= \dfrac{LP^{0.66} u_{fin}^{0.40} 1.9\times10^{-5}}{(1 - T_r)^{0.40} M_{g,M}^{1.45} v_0^{0.75}}$, $\dfrac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$

(c) Mass vaporized for ammonia.

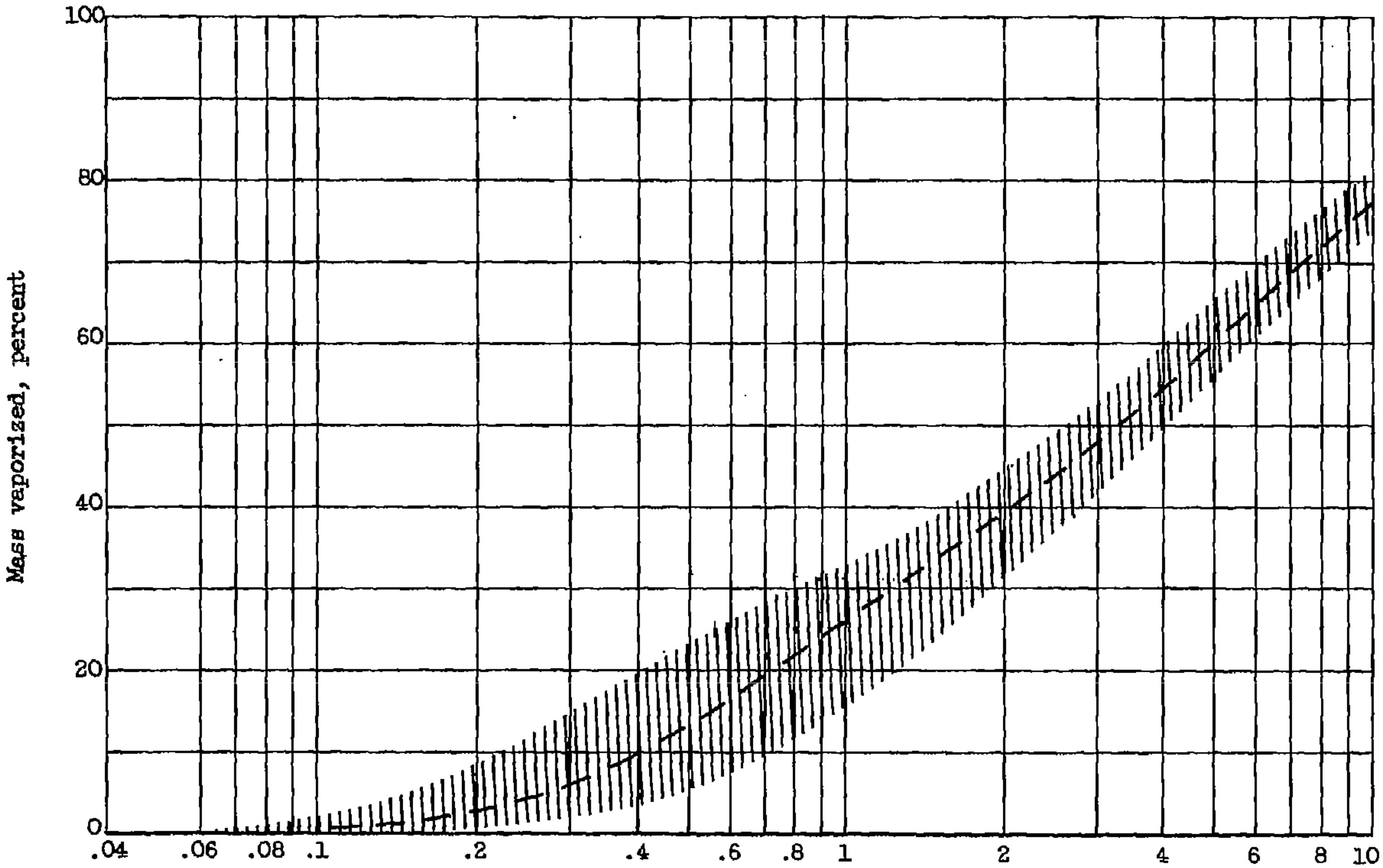
Figure 2. - Continued. Correlated results for propellant with standard deviation of 2.3.



Effective length $= \dfrac{lP^{0.66}u_{fin}^{0.40}1.9\times10^{-5}}{(1 - T_r)^{0.40}M_{g,M}^{1.45}v_0^{0.75}}, \ \dfrac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$

(d) Mass unvaporized for ammonia.

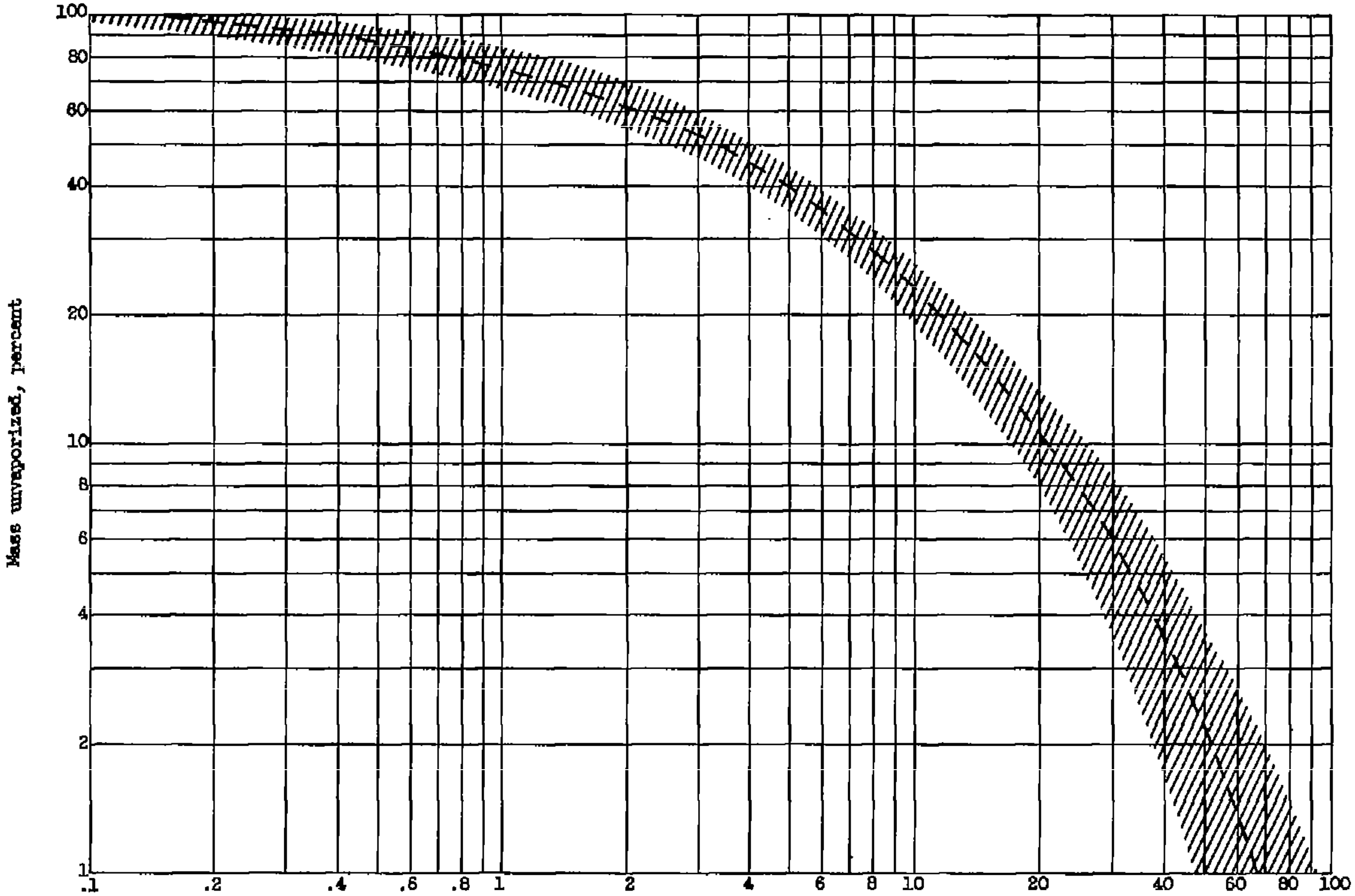
Figure 2. - Continued. Correlation results for propellant with standard deviation of 2.3.



$$\text{Effective length} = \frac{LP^{0.66}u_{fin}^{0.40}1.9\times10^{-5}}{(1 - T_r)^{0.40}M_{g,M}^{1.45}v_0^{0.75}},\ \frac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$$

(e) Mass vaporized for hydrazine sprays.

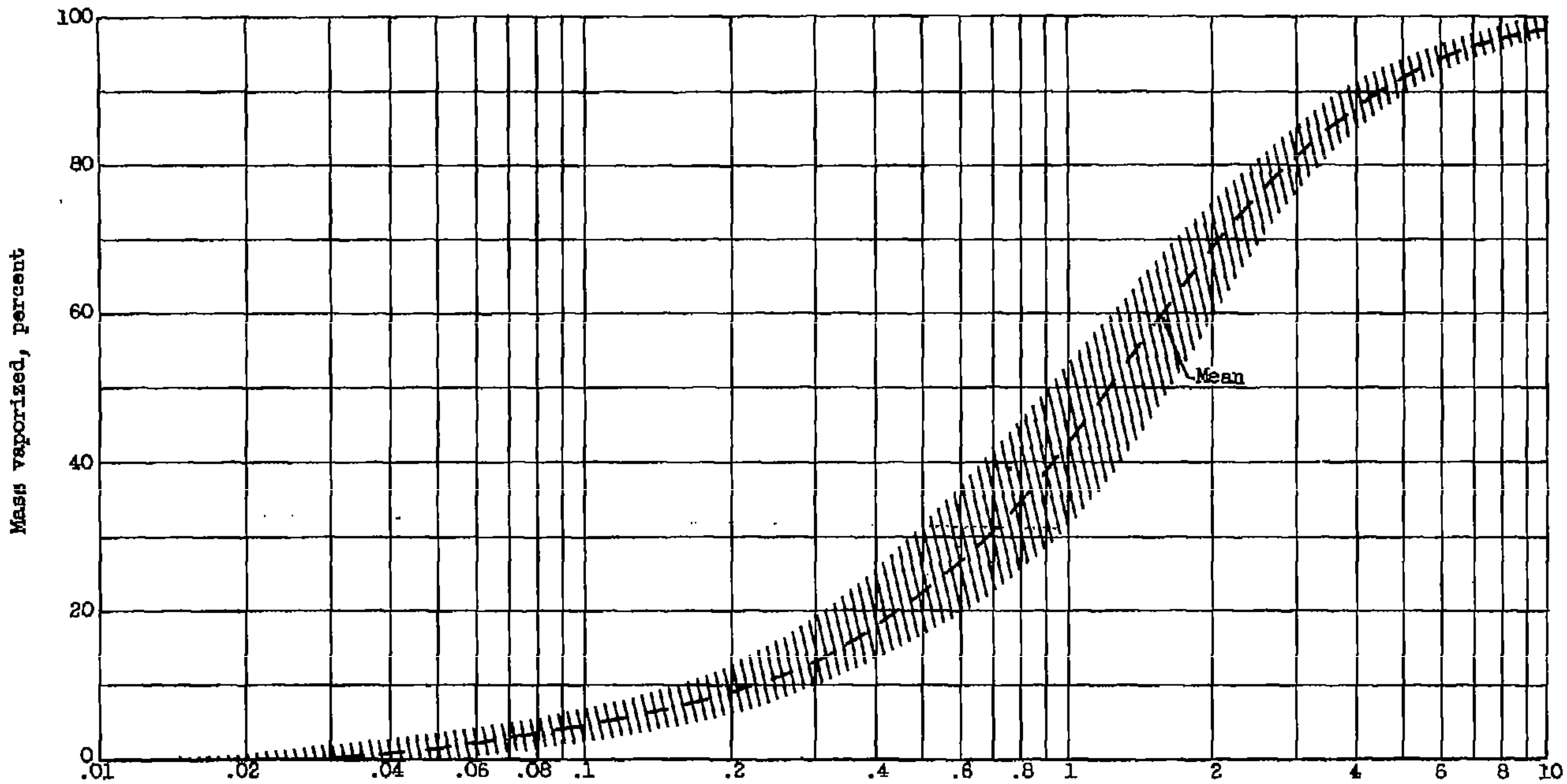
Figure 2. - Continued. Correlated results for propellant with standard deviation of 2.3.



$$\text{Effective length} = \frac{LP^{0.66} u_{fin}^{0.40} 1.9\times10^{-5}}{(1 - T_r)^{0.40} M_{g,M}^{1.45} v_0^{0.75}}, \quad \frac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$$

(f) Mass unvaporized for hydrazine sprays.

Figure 2. - Continued. Correlated results for propellant with standard deviation of 2.3.

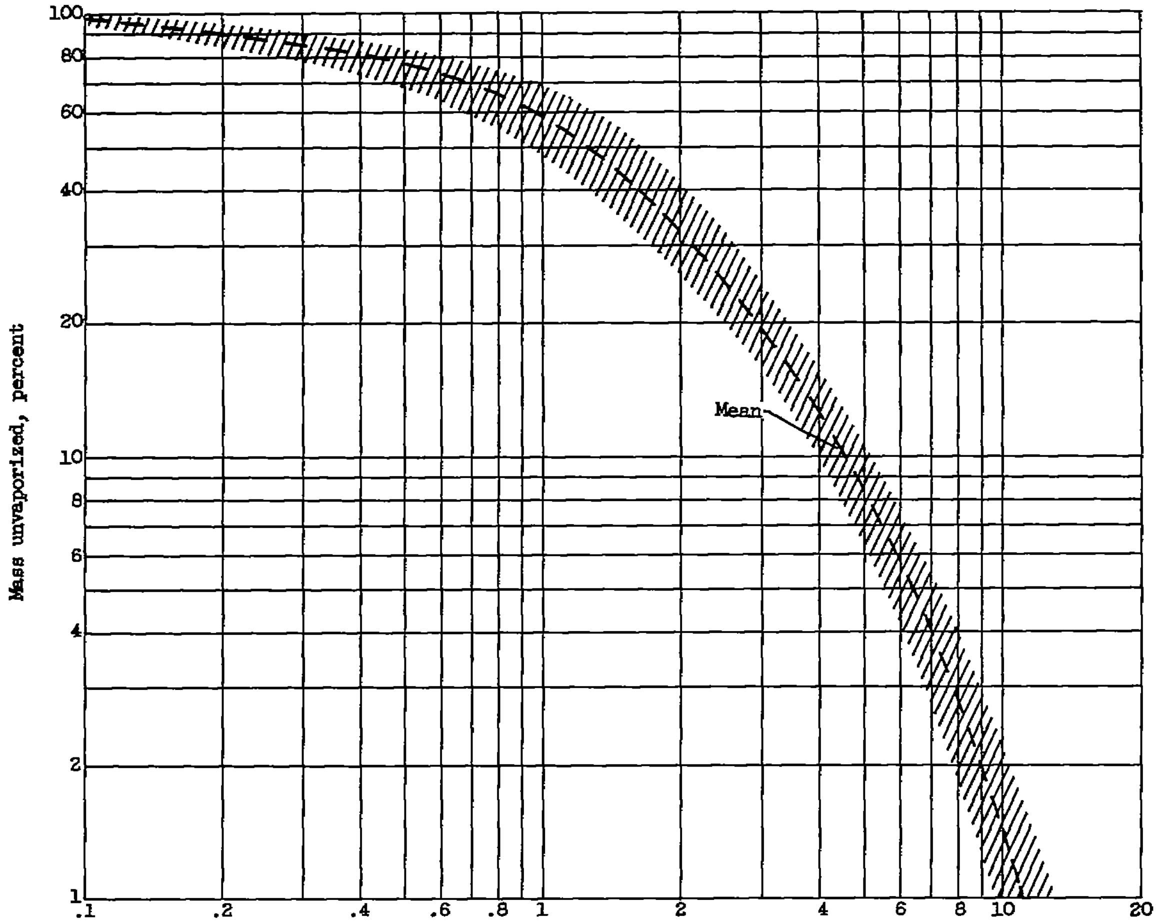


Effective length = $\dfrac{LP^{0.66}u_{fin}^{0.40}1.9\times10^{-5}}{(1-T_r)^{0.40}M_{g,M}^{1.45}v_0^{0.75}}$, $\dfrac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$

(g) Mass vaporized for liquid-oxygen sprays.

Figure 2. - Continued. Correlated results for propellant with standard deviation of 2.3.

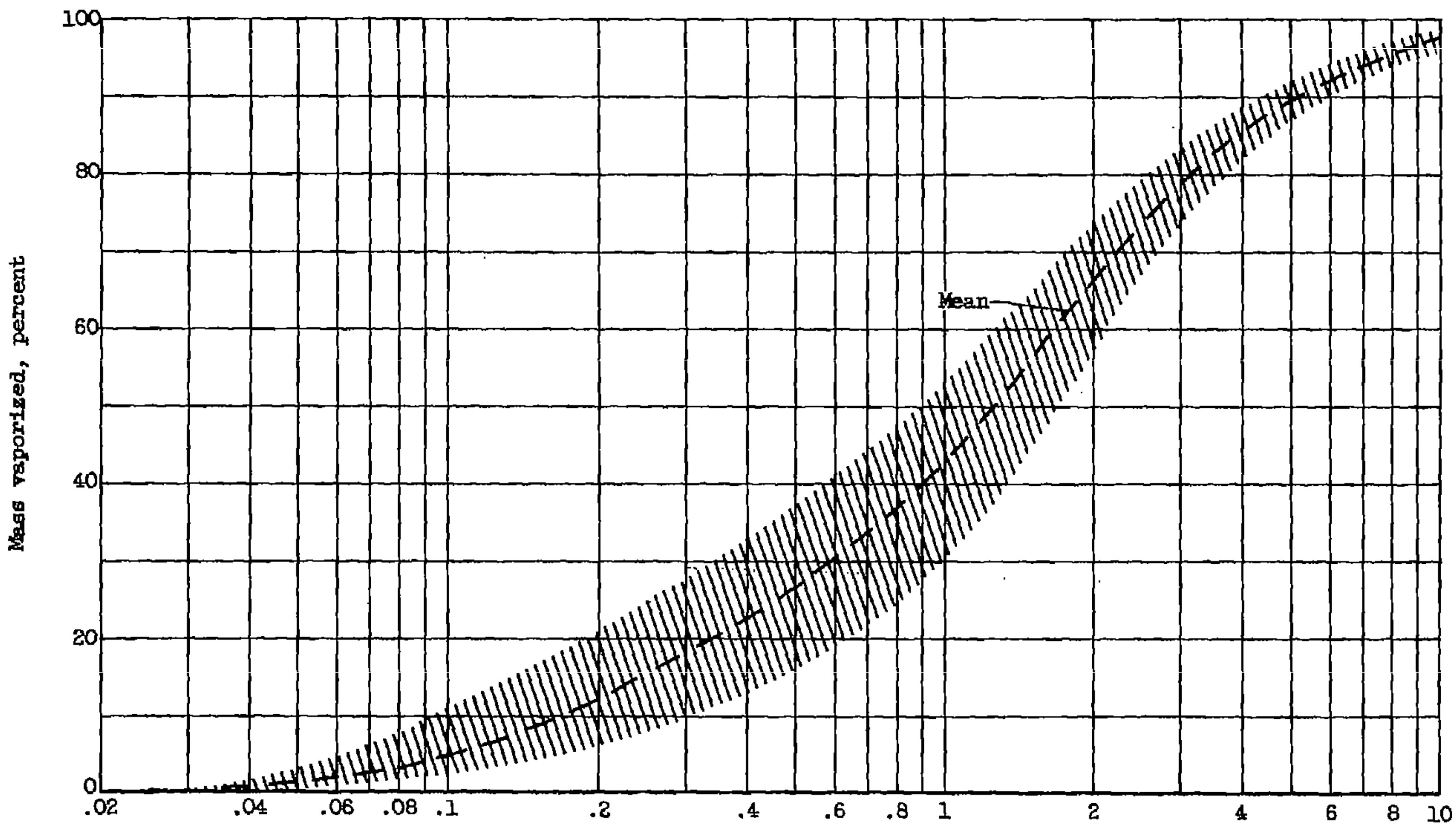
4720



Effective length = $\frac{\mathcal{L}P^{0.66}u_{fin}^{0.40}1.9\times10^{-5}}{(1-T_r)^{0.40}M_{g,M}^{1.45}v_0^{0.75}}$, $\frac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$

(h) Mass unvaporized for liquid-oxygen sprays.

Figure 2. - Continued. Correlated results for propellant with standard deviation of 2.3.

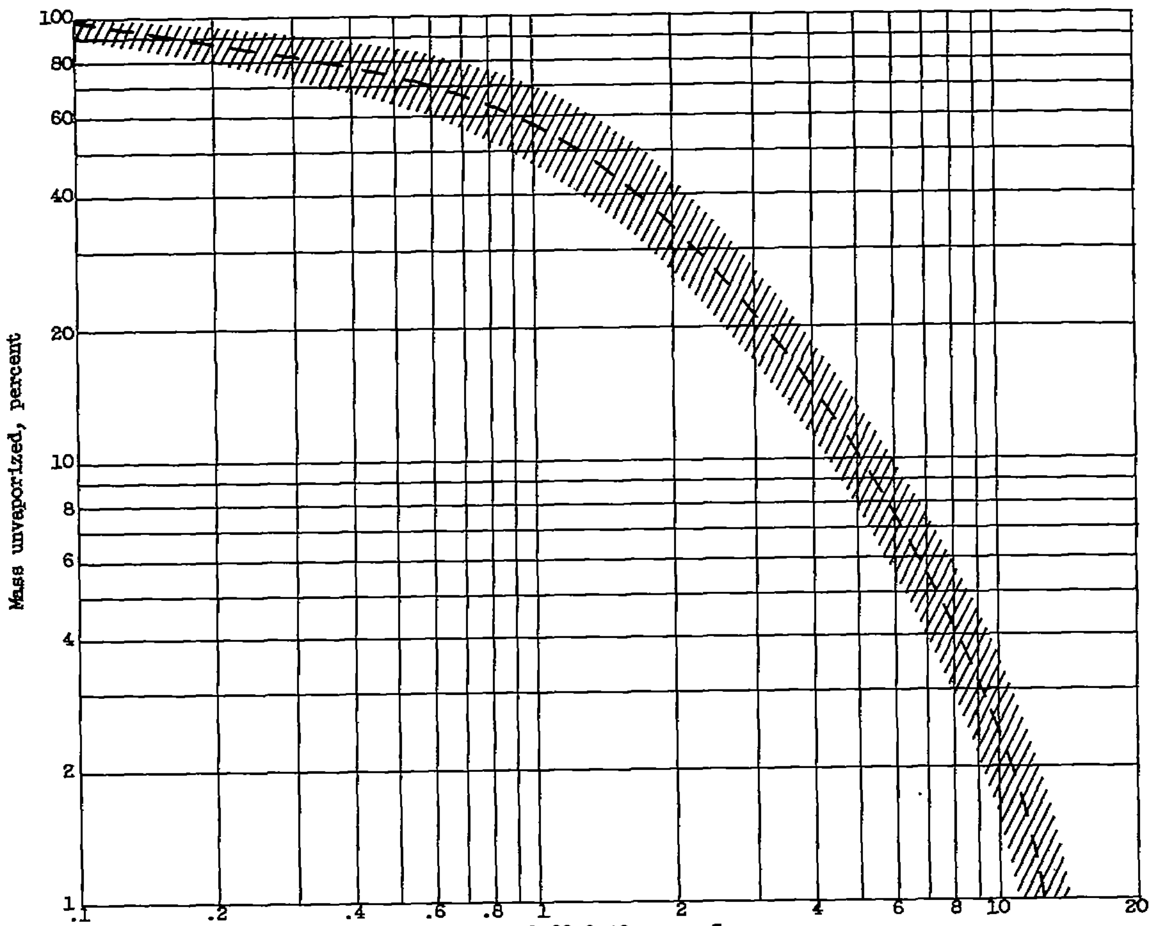


$$\text{Effective length} = \frac{LP^{0.66}u_{fin}^{0.40}1.9\times10^{-5}}{(1 - T_r)^{0.40}M_{g,M}^{1.45}v_0^{0.75}}, \quad \frac{(\text{lb})^{0.66}(\text{sec})^{0.35}}{(\text{in.})^{2.12}}$$

(i) Mass vaporized for liquid-fluorine sprays.

Figure 2. - Continued. Correlated results for propellant with standard deviation of 2.3.

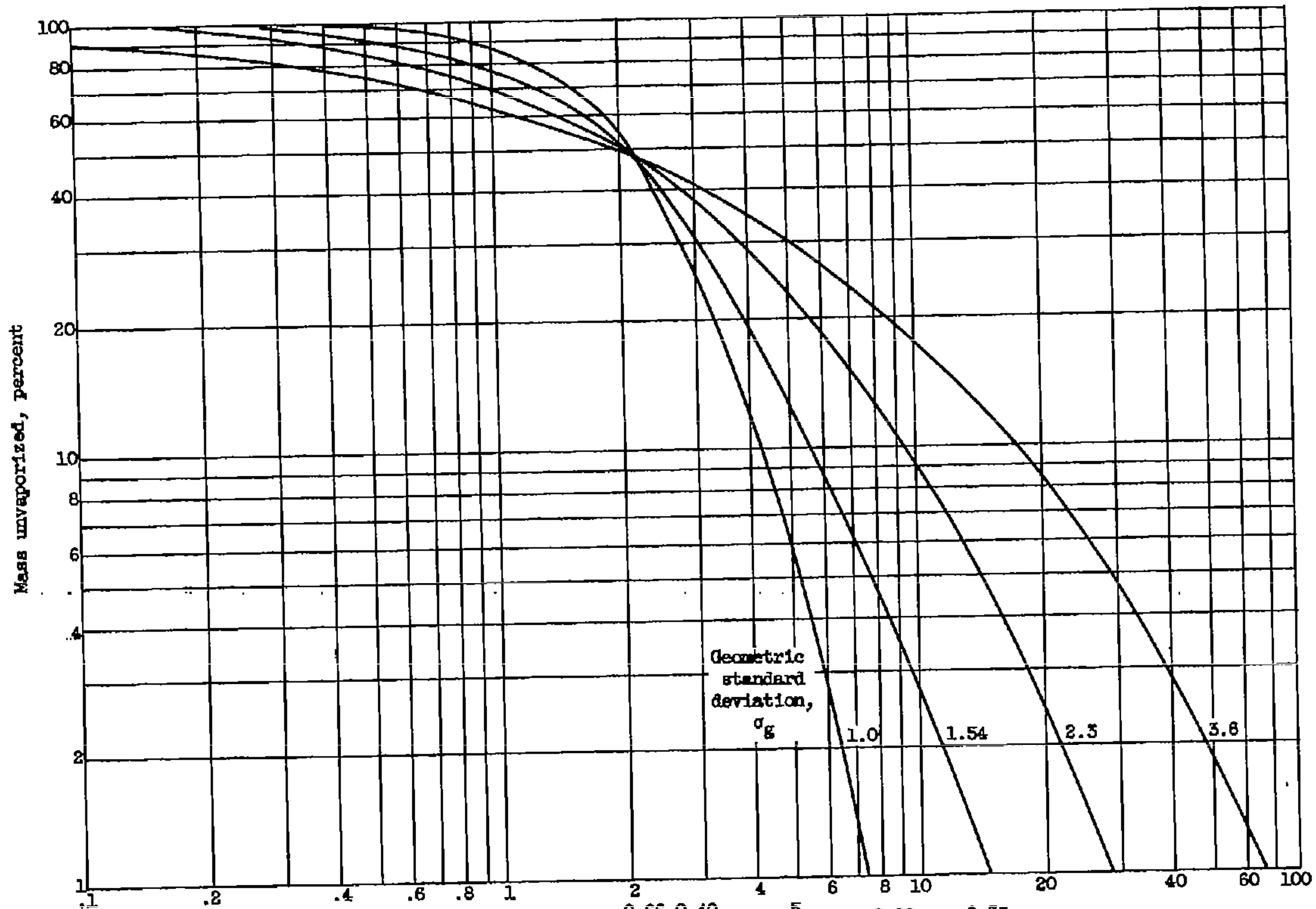
4720



Effective length = $\frac{LP^{0.66}u_{fin}^{0.40}1.9\times10^{-5}}{(1 - T_r)^{0.40}M_{g,M}^{1.45}v_0^{0.75}}$, $\frac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$

(j) Mass unvaporized for liquid-fluorine sprays.

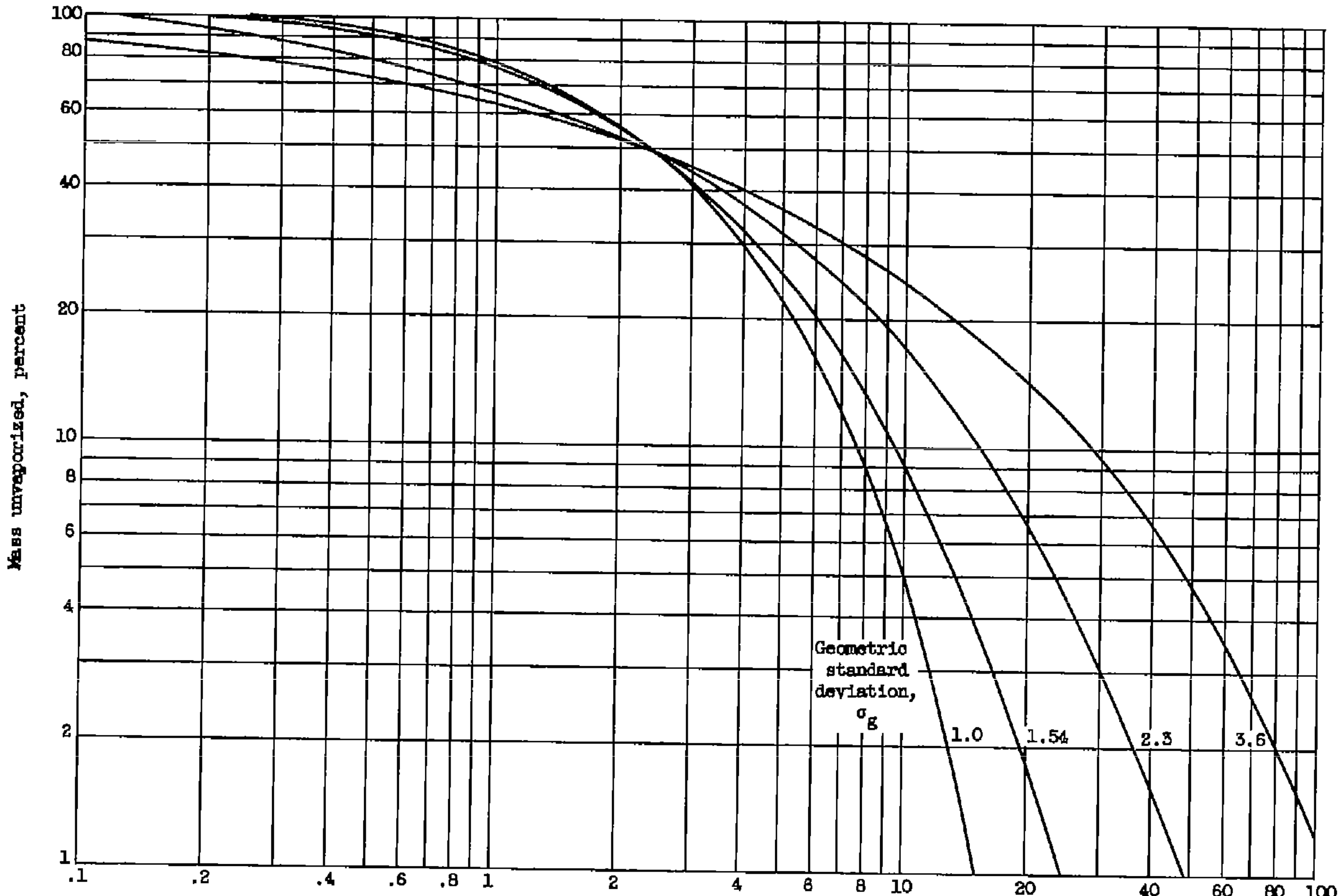
Figure 2. - Concluded. Correlated results for propellant with standard deviation of 2.3.



$$\text{Effective length} = \frac{LP^{0.66}u_{fin}^{0.40}1.9\times10^{-5}}{(1 - T_r)^{0.40}M_{g,M}^{1.45}v_0^{0.75}},\ \frac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$$

(a) Heptane.

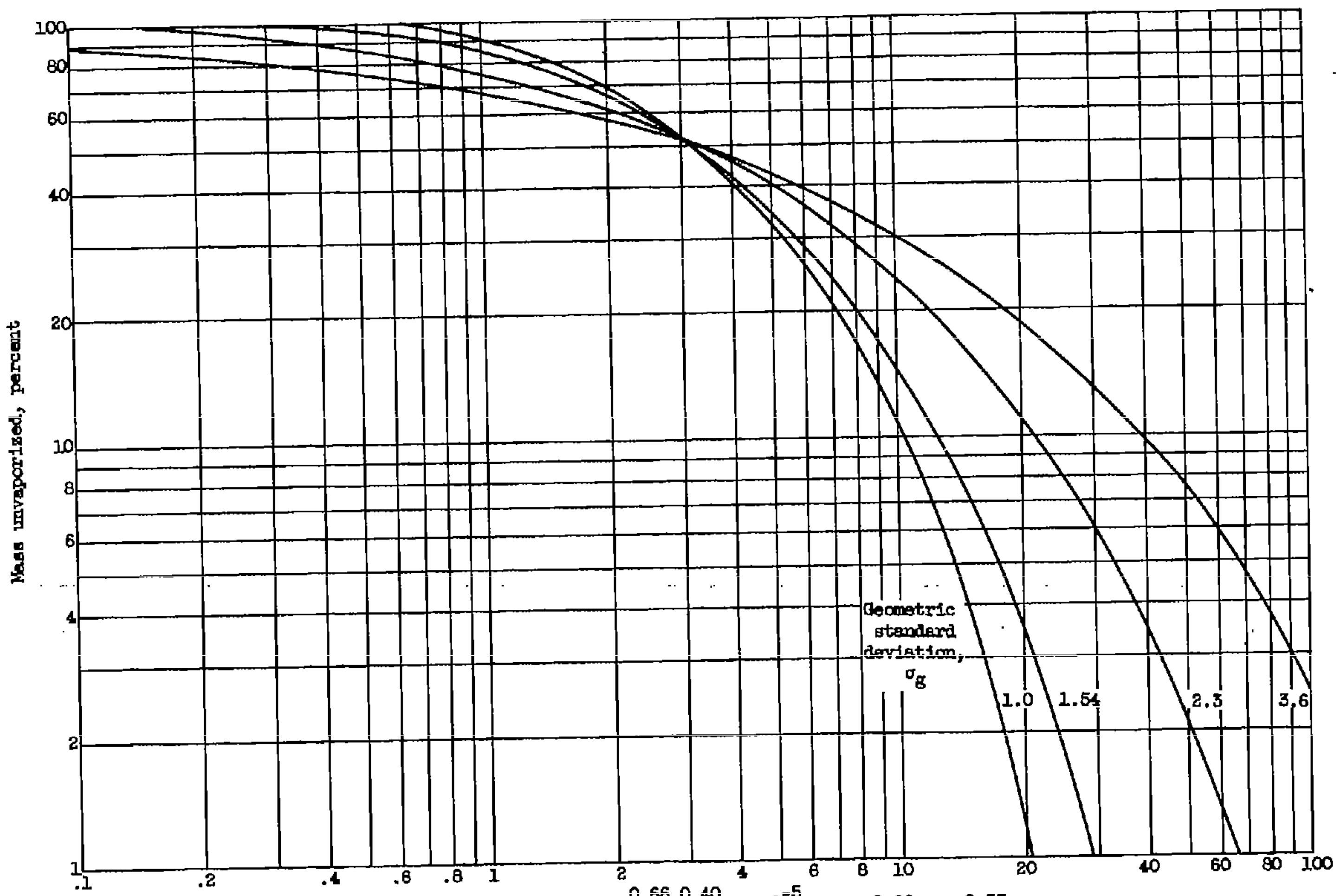
Figure 3. - Correlated results for sprays with various standard deviations.



Effective length = $\frac{LP^{0.66} u_{fin}^{0.40} 1.9\times10^{-5}}{(1 - T_r)^{0.40} M_{g,M}^{1.45} v_0^{0.75}}$, $\frac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$

(b) Ammonia.

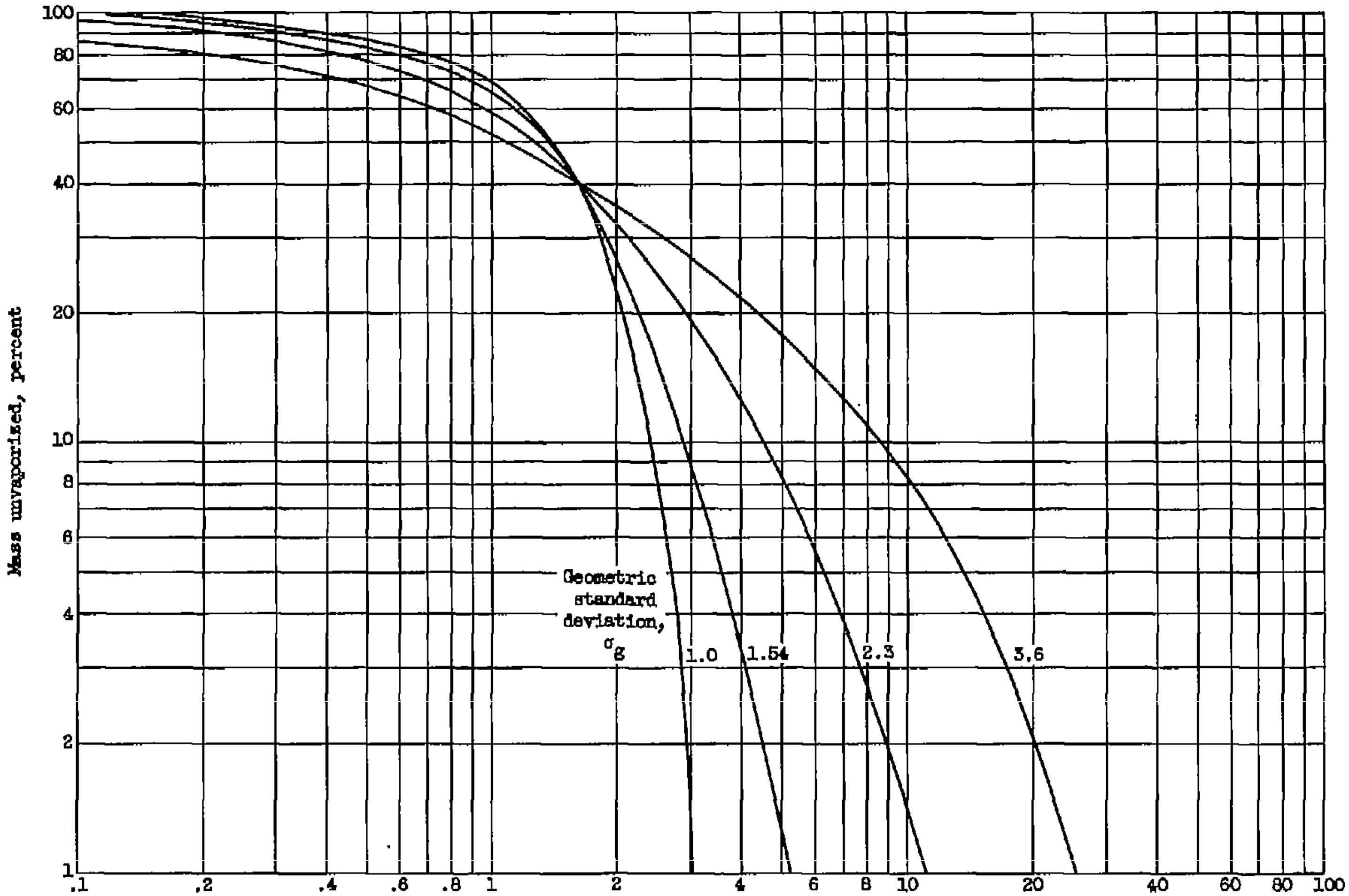
Figure 5. - Continued. Correlated results for sprays with various standard deviations.



$$\text{Effective length} = \frac{LP^{0.66} u_{fin}^{0.40} 1.9\times10^{-5}}{(1 - T_r)^{0.40} M_{g,M}^{1.45} v_0^{0.75}}, \quad \frac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$$

(c) Hydrazine.

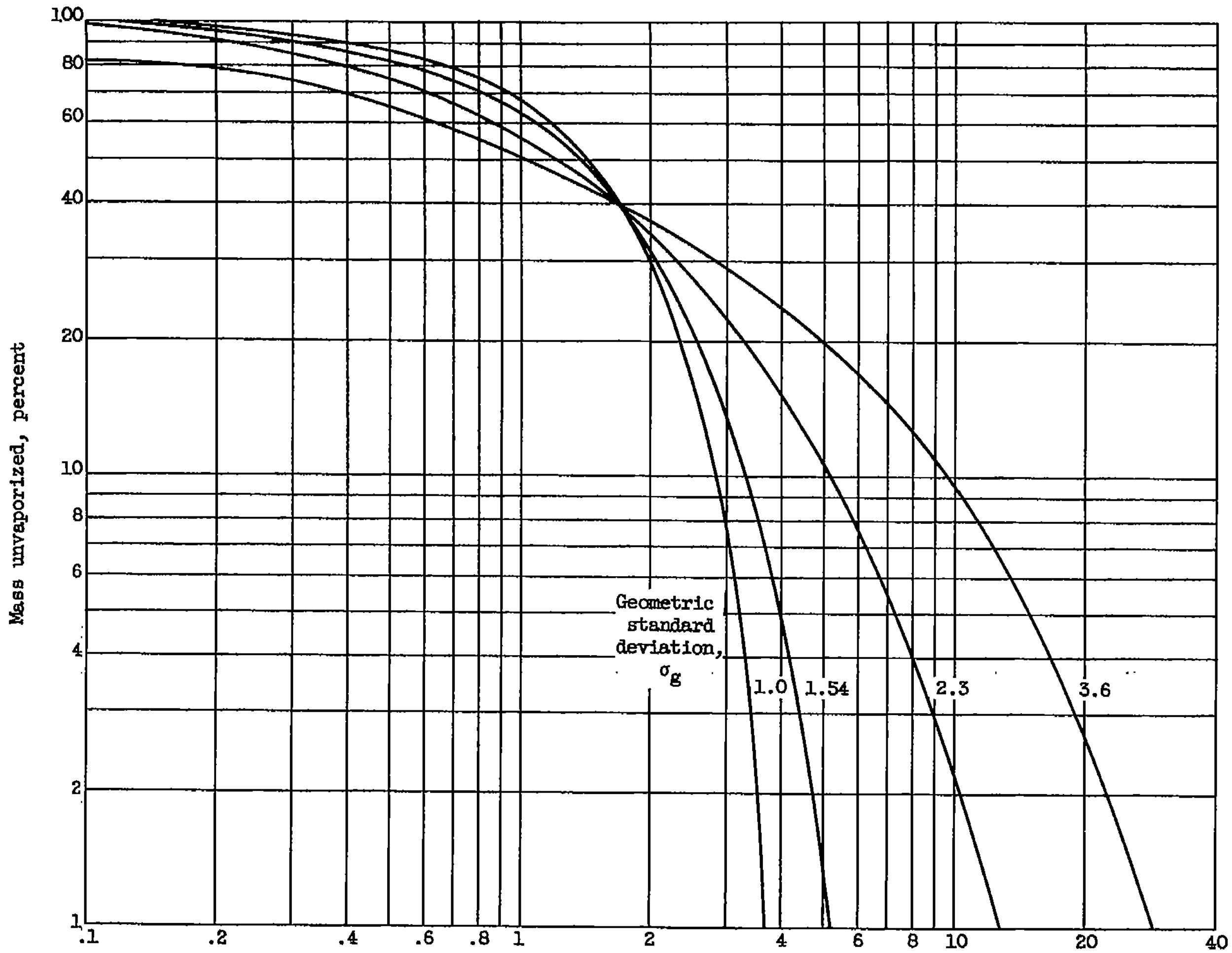
Figure 3. - Continued. Correlated results for sprays with various standard deviations.



Effective length = $\dfrac{LP^{0.66}u_{fin}^{0.40}1.9\times10^{-5}}{(1-T_r)^{0.40}M_{g,M}^{1.45}v_0^{0.75}}$, $\dfrac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$

(d) Liquid oxygen.

Figure 3. - Continued. Correlated results for sprays with various standard deviations.



$$\text{Effective length} = \frac{LP^{0.66} u_{fin}^{0.40} 1.9\times10^{-5}}{(1 - T_r)^{0.40} M_{g,M}^{1.45} v_0^{0.75}},\ \frac{(lb)^{0.66}(sec)^{0.35}}{(in.)^{2.12}}$$

(e) Liquid fluorine.

Figure 3. - Concluded. Correlated results for sprays with various standard deviations.